

# Recent results on nucleon spin structure study at RHIC

Qinghua Xu

*School of Physics, Key Laboratory of Particle Physics and Particle Irradiation (MoE), Shandong University,  
 Jinan 250100, China*

*E-mail: xugh@sdu.edu.cn*

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Both the PHENIX and STAR experiments at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory are running polarized proton–proton collisions at  $\sqrt{s} = 200$  and 500 GeV. The main goal of the RHIC spin physics program is to gain deeper insight into the spin structure of the nucleon. We will give an overview of recent spin results from RHIC, particularly the study of gluon polarization via jet/hadron production and sea quark polarization via  $W$  boson production in longitudinally polarized proton–proton collisions.

**Keywords** RHIC, nucleon spin structure, gluon polarization, sea quark polarization

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## 1 Introduction

The spin structure of the nucleon has been an hot topic in quantum chromodynamics (QCD) since the late 1980s, when polarized lepton–nucleon deep inelastic scattering (DIS) experiments revealed that only a small portion ( $\sim 20\%$ ) of the nucleon spin is carried by the spins of quarks and antiquarks [1]. According to the spin sum rule in the light cone gauge, the proton spin of one-half can be decomposed into

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g, \quad (1)$$

where  $\Delta\Sigma$  denotes the combined quark and antiquark spin contribution, and  $L_{q(g)}$  is the quark (gluon) orbital angular momentum contribution. In the past three decades, significant efforts have been made both experimentally and theoretically to elucidate the contribution of the gluon spin and the flavor-separated contribution of quarks and antiquarks, as well as the contribution of the orbital angular momentum of quarks and gluons. DIS

experiments with polarized lepton and/or hadron beams have shown that the fraction of proton spin carried by the quark and antiquark spins is relatively small, with a typical value of about one-quarter (0.25) [1]. Inclusive DIS measurements, however, provided little constraint on the gluon polarization. The current best probes of  $\Delta g$  are offered by polarized proton–proton collisions, i.e., the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory, which is the first and currently the only high-energy polarized hadron–hadron collider in the world. On the other hand, the polarized proton–proton collider can provide a cleaner probe of the flavor separation of quark and antiquark polarization via parity-violating weak boson production than the semi-inclusive DIS (SIDIS) process, which suffers from uncertainty of the fragmentation functions.

Polarized proton–proton collisions at center-of-mass energies of 200 and 500 GeV at RHIC provide a unique way to gain new insights into the proton spin structure, especially the gluon polarization and sea quark polarization in the nucleon, as mentioned above [2]. There are two main experiments (detectors) for the spin program at RHIC: PHENIX and STAR. Both are carrying out a rich spin program using longitudinally polarized and transversely polarized proton–proton collisions.

For precise determination of the gluon polarization ( $\Delta g$ ), the STAR detector is well suited for the reconstruction of various final states including jets, identified hadrons ( $\pi^0$ ,  $\pi^\pm$ ), electrons/positrons, and photons, which allows for measurements of different gluon–

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involved processes. The recent STAR results on the inclusive jet double-spin asymmetry provide the first evidence of a nonzero gluon polarization in the Bjorken- $x$  range  $x > 0.05$ , and the magnitude is even comparable to the total quark spin contribution, as indicated in the recent global analysis.

Another main objective of the STAR spin program is flavor separation of the quark and antiquark spin to the proton spin via  $W$  boson production in polarized proton-proton collisions at  $\sqrt{s} = 500$  GeV. The parity-violating nature of the  $W$  boson provides a unique and clean way of measuring the anti- $u$  and anti- $d$  quark polarization without the involvement of hadronization as in the SIDIS process. The recent results of  $W$  boson single-spin asymmetry from the 2012 data at STAR, which provide new constraints on light sea quark polarization, will be discussed.

## 2 Gluon polarization ( $\Delta G$ ) measurements

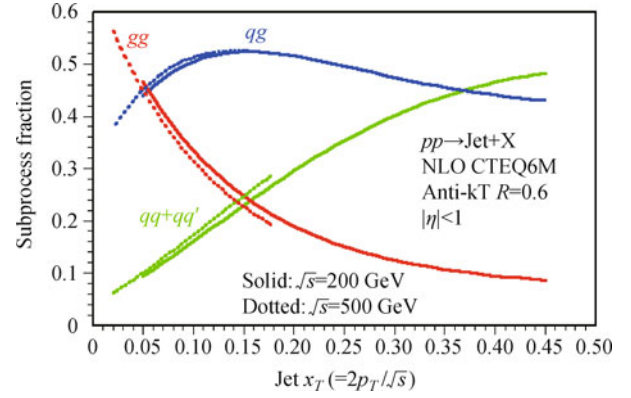
In proton-proton collisions, the gluon polarization can be accessed with strongly interacting probes including jet or hadron production by measuring the double-spin asymmetries ( $A_{LL}$ ),

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{1}{P_1 P_2} \frac{N^{++} - R N^{+-}}{N^{++} + R N^{+-}}, \quad (2)$$

where  $\sigma_{++/--}$  denotes the cross section for jet/hadron production with proton beam helicity of “++/--”,  $P_1$  and  $P_2$  are the beam polarizations,  $R = \mathcal{L}^{++}/\mathcal{L}^{+-}$  is the ratio of the luminosities, and  $N^{++}$  ( $N^{+-}$ ) are the jet or hadron yields for equal (opposite) helicity beams. To see how  $A_{LL}$  provides sensitivity to the gluon polarization, at the leading order the asymmetry can be described as

$$A_{LL} = \frac{\sum_{f_a, f_b} \Delta f_a \times \Delta f_b \times d\hat{\sigma}^{f_a f_b \rightarrow fX} \cdot \hat{a}_{LL}^{f_a f_b \rightarrow fX}}{\sum_{f_a, f_b} f_a \times f_b \times d\hat{\sigma}^{f_a f_b \rightarrow fX}}, \quad (3)$$

where  $\Delta f_{a(b)}$  denotes the helicity distribution function for parton  $a(b)$ ,  $f_{a(b)}$  is the unpolarized parton distribution function, and  $\hat{a}_{LL}^{f_a f_b \rightarrow fX}$  is the double-spin asymmetry for the partonic process  $f_a f_b \rightarrow fX$ . The summation considers all the subprocesses, including  $qq$ ,  $qg$ , and  $gg$  scattering. For most RHIC kinematics,  $qg$  and  $gg$  scatterings dominate the jet production [3, 4], making  $A_{LL}$  measurements for jets and hadrons sensitive to the gluon polarization, as shown in Fig. 1 for the fractional contributions of different subprocesses to the inclusive jet production in  $pp$  collisions at 200 and 510 GeV [5]. The measured  $A_{LL}$  versus jet transverse momenta cover

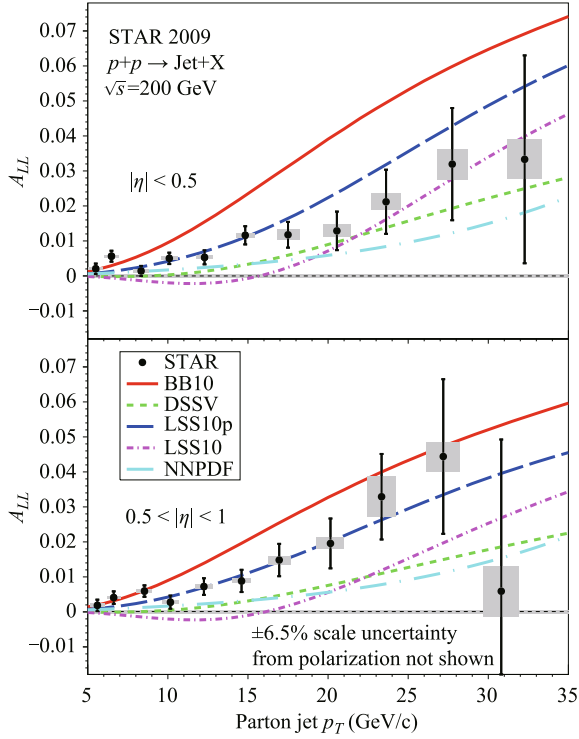


**Fig. 1** Relative contributions from different partonic subprocesses to inclusive jet production as a function of  $x_T (= 2p_T/\sqrt{s})$  at mid-rapidity at 200 and 510 GeV in  $pp$  collisions [5].

a wide range of the parton momentum fraction  $x$  of the proton, with a combination of different subprocesses. Ultimately, the data will be included in the global analysis, together with data on other processes such as DIS, to constrain the gluon polarization as different groups have done [6–10], similar to the unpolarized case.

At STAR, jets were reconstructed from charged tracks with  $|\eta| < 1.3$  measured in the Time Projection Chamber (TPC) and energy deposits in the Barrel Electromagnetic Calorimeter (BEMC) with towers at  $|\eta| < 1$  and the End-cap Electromagnetic Calorimeter (EEMC) at  $1 < \eta < 2$ . The jets were reconstructed using the midpoint cone algorithm [11] for early data and then the anti- $k_t$  algorithm [12] (known as infrared-safe) was chosen as the jet algorithm at STAR since run 9 data. The jet cross section measurement and the first  $A_{LL}$  measurements of inclusive jets were done using 2003 and 2004 data at STAR [13], and inclusive jet production can be well described by pQCD. Updated measurements of  $A_{LL}$  with higher precision using 2005 and 2006 data have also been published [14, 15]. STAR also measured the double-spin asymmetries for  $\pi^0$  at  $|\eta| < 1$  [16] and the near-forward rapidity at  $1 < \eta < 2$  [17]. The early  $A_{LL}$  results were included in the DSSV2008 QCD global analysis to provide information on the gluon polarization and ruled out large positive and negative scenarios with a small value of  $\Delta g$  in the range of  $0.05 < x < 0.2$ , resulting in a small gluon polarization within the uncertainties [7].

After the 2006 run, several improvements at STAR, including an increase in the jet trigger efficiency and a faster data acquisition system, enabled us to improve the  $A_{LL}$  precision significantly during the 2009 run. Figure 2 shows the  $A_{LL}$  results for inclusive jet production versus jet  $p_T$  in two pseudo-rapidity bins for the 2009 data [18] at STAR; theoretical predictions with inputs from different global analyses are also shown for comparison. These predictions were made by inserting the polarized



**Fig. 2** Longitudinal double-spin asymmetry  $A_{LL}$  for inclusive jet production vs. jet  $p_T$  for  $|\eta| < 1$  in  $pp$  collisions at 200 GeV at STAR [18].

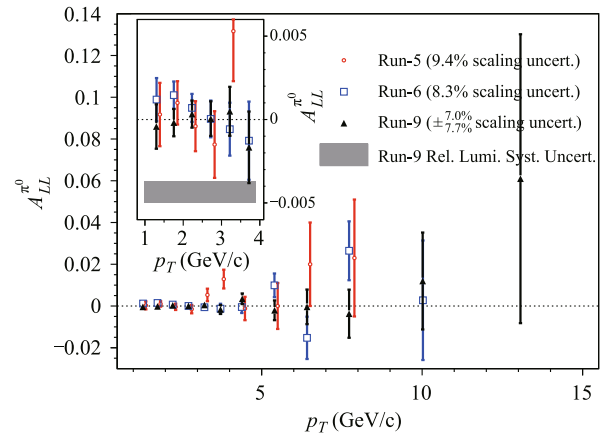
parton distribution functions (PDFs) from BB [6], DSSV [7, 8], LSS [9], and NNPDF [10] into the NLO jet production code of Mukherjee and Vogelsang [4]. The BB10 and NNPDF polarized PDFs are based only on inclusive DIS data, whereas that of LSS includes both inclusive and SIDIS data sets. The LSS10 gluon density has a node at  $x \simeq 0.2$ , and the LSS10p gluon is positive definite at the input scale  $Q_0^2 = 2.5 \text{ GeV}^2$ . The DSSV [7] model, in addition to DIS and SIDIS data, also incorporates RHIC polarized proton–proton data before 2009. LSS10p provides the best description of these STAR jet data, whereas the STAR results are higher than the predictions of DSSV and NNPDF and below the predictions of BB10. However, the measurements fall within the combined data and model uncertainties for these three cases.

The impact of new STAR jet data on constraining the gluon polarization was studied using the reweighing method by the NNPDF group [19] and the truncated  $x$ -integral of  $\Delta g(x, Q^2 = 10 \text{ GeV}^2) = 0.17 \pm 0.06$  in the range  $0.05 < x < 0.2$ , which was  $0.05 \pm 0.15$ , as a comparison before having the 2009 STAR jet data. The STAR jet  $A_{LL}$  data are found to be consistent with the PHENIX  $\pi^0$   $A_{LL}$  values [20], as shown in Fig. 3, which are very small or consistent with zero within the uncertainty but cover a different scale range. The DSSV group also updated their global analysis by incorporating the

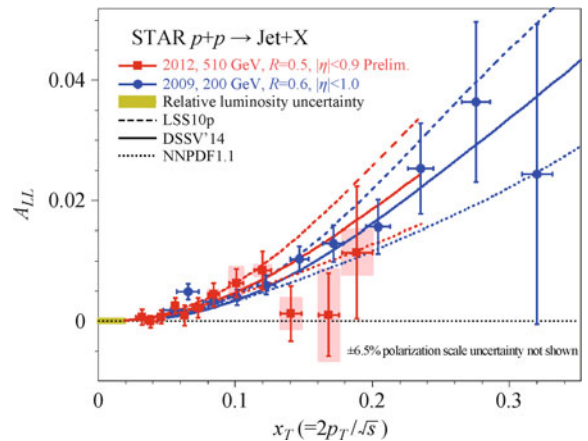
2009  $A_{LL}$  results from the STAR inclusive jet channel and PHENIX  $\pi^0$  channel, which suggested a consistent sizable value of the gluon polarization at the level of  $\int_{0.05}^1 \Delta g dx (Q^2 = 10 \text{ GeV}^2) = 0.20^{+0.06}_{-0.07}$  [21], which is of similar magnitude as the total quark spin contribution itself.

In addition, STAR recently released new results on jet  $A_{LL}$  in  $pp$  collisions at 510 GeV, which cover a smaller  $x$  range and provide new constraints on the gluon polarization at low  $x$ . Figure 4 shows  $A_{LL}$  versus  $x_T$  for inclusive jet production at mid-rapidity at 510 GeV in  $pp$  collisions from 2012 STAR data [5], together with the results at 200 GeV, in comparison with theoretical predictions.

Di-jet production will allow a better constraint on the partonic kinematics to determine the shape of the gluon polarization. The partonic Bjorken- $x$  of the incoming partons can be extracted at leading order from the



**Fig. 3** Longitudinal double-spin asymmetry  $A_{LL}$  for  $\pi^0$  production vs.  $p_T$  for  $|\eta| < 1$  in  $pp$  collisions at 200 GeV at PHENIX [20].



**Fig. 4** Inclusive jet  $A_{LL}$  vs.  $x_T (= 2p_T/\sqrt{s})$  at mid-rapidity at 510 and 200 GeV in  $pp$  collisions at STAR, compared to recent NLO predictions. Red (blue) data points and curves represent 200 (510) GeV.

pseudo-rapidity plus the transverse momentum of the di-jets. The wide acceptance of the STAR experiment permits reconstruction of di-jet events with different topological configurations. Future inclusive and di-jet  $A_{LL}$  measurements at both  $\sqrt{s} = 200$  and 500 GeV at STAR will extend the range toward smaller values of Bjorken- $x$ .

### 3 Sea quark polarization measurements

While the valence quark helicity distributions are well determined at intermediate  $x$  from DIS experiments, the polarization of the sea quarks  $\bar{u}$  and  $\bar{d}$  is not well constrained by SIDIS data, especially regarding whether the light sea symmetry is broken as in the unpolarized case [22]. The production of  $W^{+(-)}$  bosons in  $pp$  collisions with beams longitudinally polarized provides a perfect tool to access sea quark and valence quark helicity distributions without the need for hadron fragmentation functions. As  $W$  production is a parity-violating process,  $W$  bosons couple only to either left-handed particles or right-handed antiparticles, thus selecting only the corresponding helicity-positive or -negative quark and antiquark from the polarized proton. The longitudinal single-spin asymmetry  $A_L$  for  $W$  boson production with one proton beam polarized is defined as

$$A_L(W) \equiv \frac{\sigma(p_+p \rightarrow W) - \sigma(p_-p \rightarrow W)}{\sigma(p_+p \rightarrow W) + \sigma(p_-p \rightarrow W)}, \quad (4)$$

where  $\sigma_+/\sigma_-$  is the cross section with a helicity positive/negative proton beam.

As the production of  $W$  bosons violates parity maximally, the above  $A_L$  equation for  $W^\pm$  can be rewritten as follows at leading order:

$$A_L^{W^+} \equiv \frac{\Delta u(x_1)\bar{d}(x_2) - \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}, \quad (5)$$

$$A_L^{W^-} \equiv \frac{\Delta d(x_1)\bar{u}(x_2) - \Delta\bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)}. \quad (6)$$

We can see that  $A_L^{W^+}$  approaches  $\Delta u/u$  in the limit  $y_W \gg 0$ , as the rapidity along the polarized proton beam is defined as positive, and the valence quark usually carries a larger momentum fraction. Similarly,  $A_L^{W^+}$  approaches  $-\Delta\bar{d}/\bar{d}$  when  $y_W \ll 0$ . Thus, by identifying the rapidity of the  $W$  bosons, we can measure the polarizations of quark and antiquarks directly. For  $W^-$ ,  $\Delta\bar{u}/\bar{u}$  can be accessed in the backward region accordingly.

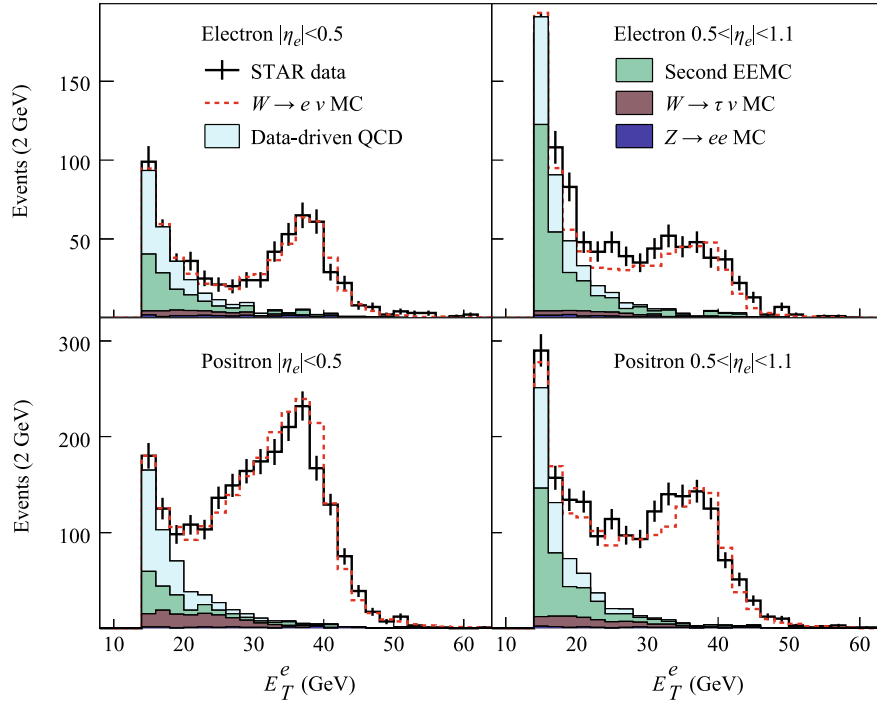
In experiments,  $W^\pm$  is usually detected via the leptonic channel with the kinetics of lepton decay, as the missing energy of the neutrino is hard to measure. The theoretical framework that describes inclusive lepton

production of  $W$  bosons has been developed, so the measurements of  $A_L$  versus the lepton rapidity can be compared with theoretical predictions [27, 28]. The first measurements of the spin asymmetry,  $A_L$ , and cross section for  $W^\pm$  production were reported by the STAR [23, 25] and PHENIX [24] experiments using data collected in 2009 at  $\sqrt{s} = 500$  GeV. These measurements paved the way for further measurements with larger statistics and more pseudo-rapidity bins that will provide real constraints on  $\bar{u}$  and  $\bar{d}$  polarization in the nucleon.

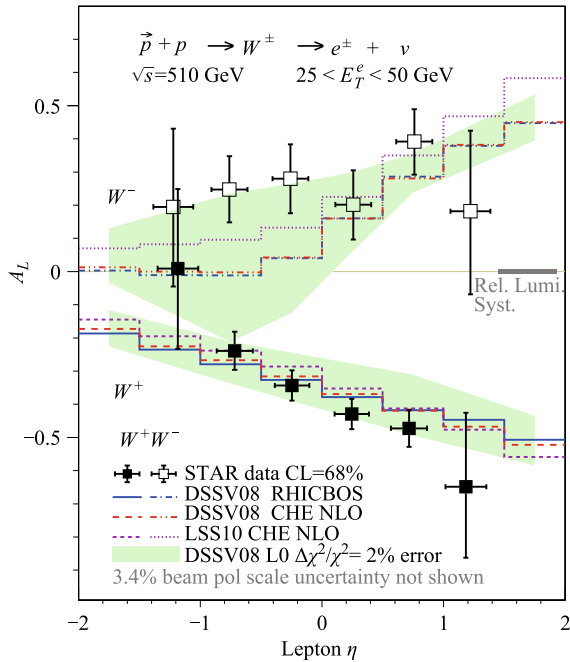
At STAR,  $W^{+(-)}$  are detected through  $e^{+(-)}$  with large transverse momentum via the  $W \rightarrow e\nu$  channel with the BEMC and EEMC. The  $W \rightarrow e\nu$  events are characterized by an isolated  $e^\pm$  with a sizable transverse energy,  $E_T^e$ , that peaks near half the  $W$  mass ( $\sim 40$  GeV, referred to as the Jacobian peak). The neutrino from  $W$  decay, close to opposite in the azimuthal of decay  $e^\pm$ , with a large missing transverse energy, is undetected, which causes a large imbalance in the  $p_T$  sum of all the reconstructed final state particles. A  $p_T$ -balance variable is defined in terms of the  $p_T$  sum of the  $e^\pm$  candidate and the reconstructed jets outside an isolation cone around the electron track with a radius  $\Delta R = 0.7$ . This signed  $p_T$ -balance must be larger than a typical value of 14 GeV/c for the 2011 and 2012 data. Charge separation of  $W^+$  and  $W^-$  is implemented on the basis of the  $e^\pm$  track curvature measured in the TPC. The  $W^\pm$  yield versus the  $e^\pm$  transverse energy  $E_T$  is shown in Fig. 5.

In 2012, the STAR experiment collected  $pp$  data with an integrated luminosity of 72 pb $^{-1}$  at  $\sqrt{s} = 510$  GeV and an average beam polarization of 56%, which is six times larger than that in the 2009 dataset, thus allowing a pseudo-rapidity-dependent measurement of  $A_L$  for  $W$  bosons. In 2011, STAR also collected a relatively small data sample with an integrated luminosity of 11 pb $^{-1}$  with a similar beam polarization. The  $A_L$  results from the STAR 2011+2012 data [26] are shown in Fig. 6 for both  $W^+$  and  $W^-$  versus the lepton pseudo-rapidity, with comparisons to theoretical predictions from NLO (CHE) [27] and fully resummed (RHICBOS) [28] calculations based on the DSSV08 helicity distributions [7]. The  $A_L^{W^+}$  data are in good agreement with the predictions using the DSSV08 global analysis. However, the measured  $A_L^{W^-}$  asymmetries are systematically larger than the theoretical predictions using the DSSV08 analysis, especially for  $\eta_{e^-} < -0.5$ , which indicates that these data provide new constraints for  $\Delta\bar{u}$  compared to those from previous data. The region of  $\eta_{e^-} < -0.5$  in particular is expected to be sensitive to the  $\bar{u}$  quark helicity distribution; hence, the enhancement of  $A_L^{W^-}$  there suggests a sizable positive  $\bar{u}$  quark polarization relative to that expected from the global analysis of polarized DIS





**Fig. 5**  $E_T^e$  distribution for  $W^-$  (top row) and  $W^+$  (bottom row) candidates (black), background contributions, and the sum of background and  $W \rightarrow e + \nu_e$  Monte Carlo (MC) signals (red dashed) in  $pp$  collisions at STAR.



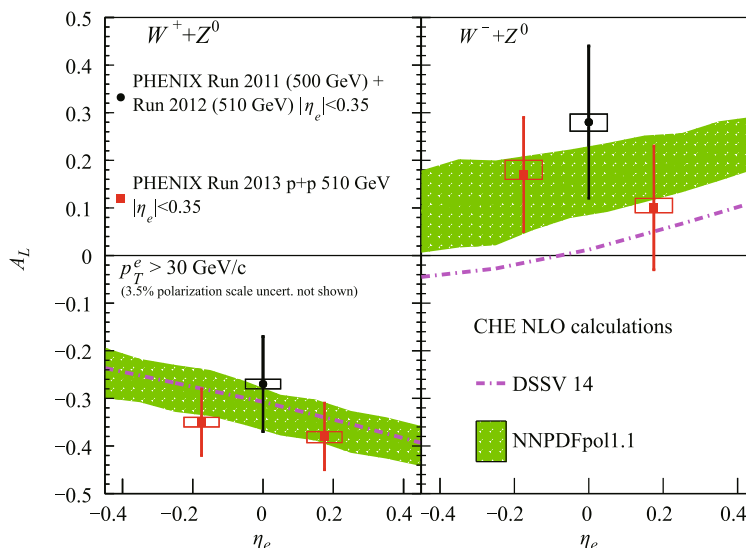
**Fig. 6** Single-spin asymmetry  $A_L$  for  $W^\pm + Z^0$  production as a function of  $\eta_e$  in  $pp$  collisions at 510 GeV at STAR using 2011+2012 data [26].

data. These results provide the first clear evidence that the flavor symmetry is also broken in the polarized light sea quark, where  $\Delta\bar{u}$  is positive and  $\Delta\bar{d}$  is negative. The very recent DSSV<sup>++</sup> global analysis including the new RHIC data, in particular the STAR 2012  $W$   $A_L$  results,

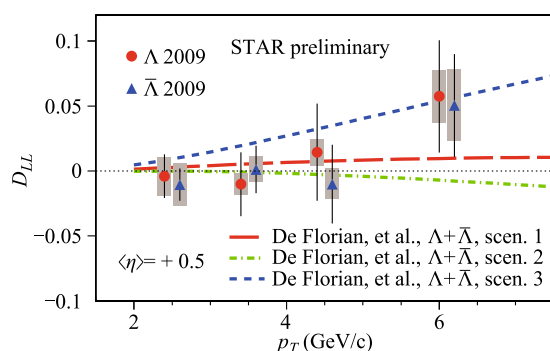
shows a significant shift from negative to positive for the best-fit value of  $\Delta\bar{u}$  with an integral of  $0.05 < x < 1$  [29]. A first unbiased global determination of polarized parton distribution by the NNPDF group [19], also confirmed the above conclusions, even though they did not include any SIDIS data.

The PHENIX experiment also published its measurements on the single-spin asymmetry  $A_L$  for  $W^\pm$  production as a function of  $\eta_e$  in  $pp$  collisions at 510 GeV using 2011, 2012, and 2013 data [30], which cover only the mid-rapidity range, and the  $A_L$  results are consistent with the STAR results mentioned above in the same rapidity range. RHIC-STAR completed a long successful longitudinally polarized  $p + p$  run at  $\sqrt{s} = 510$  GeV in 2013 with an integrated luminosity of more than  $300 \text{ pb}^{-1}$ ; the new results will be available very soon and will further constrain the flavor-separated antiquark contributions to the proton spin.

The longitudinal spin transfer  $D_{LL}$  of  $\Lambda$  and  $\bar{\Lambda}$  hyperons in  $pp$  collisions is expected to be sensitive to the helicity distribution function of strange (anti)quarks and to the polarized fragmentation functions [31, 32]. A first proof-of-principle measurement of  $D_{LL}$  at mid-rapidity has been performed with STAR data taken in 2005 [33]. In 2009, an eightfold larger data sample was collected at STAR; the  $D_{LL}$  analysis of this data sample extended the hyperon transverse momentum with better precision. Figure 8 shows the obtained  $D_{LL}$  results for  $\Lambda$  and  $\bar{\Lambda}$



**Fig. 7** Single-spin asymmetry  $A_L$  for  $W^\pm$  production as a function of  $\eta_e$  in  $pp$  collisions at 510 GeV at PHENIX using 2011, 2012, and 2013 data [30].



**Fig. 8** Longitudinal spin transfer  $D_{LL}$  for  $\Lambda$  and  $\bar{\Lambda}$  in polarized proton-proton collisions at  $\sqrt{s} = 200$  GeV for positive  $\eta$  vs.  $p_T$ . The curves correspond to  $D_{LL}$  predictions for  $\Lambda + \bar{\Lambda}$  based on different models of the polarized fragmentation functions [31].

versus  $p_T$  for  $0 < \eta < 1.2$  in  $pp$  collisions at 200 GeV [34].

The data extend out to  $p_T = 6$  GeV/ $c$  with a statistical uncertainty of about 0.04. The model evaluations of  $D_{LL}$  [31] for the combination of  $\Lambda$  and  $\bar{\Lambda}$  are consistent with the data and span a range of values that is similar to the experimental uncertainties.

## 4 Summary and outlook

RHIC, currently the only polarized hadron-hadron collider in the world, continues its efforts to deepen our understanding of the nucleon spin structure. New results from 2009 data on the jet double-spin asymmetry  $A_{LL}$  at RHIC-STAR in polarized proton-proton collisions at 200 GeV suggest a sizable gluon spin contribution comparable to the quark spin contribution itself. Future jet measurements will double the available data set at 200

GeV and also allow for a high statistics measurement at 500 GeV to provide constraints on  $\Delta g$  at lower  $x$ . Recent measurement of the single-spin asymmetry  $A_L$  for  $W^\pm$  production from 2011+2012 data at STAR, with a data sample about six times larger than that used for the first  $W$  measurement, have demonstrated new constraints on the antiquark helicity distributions  $\Delta\bar{u}$  and  $\Delta\bar{d}$ . Future measurements, in particular the much larger data sample taken in 2013 at RHIC, will further constrain the gluon polarization and the flavor-separated antiquark contributions to the proton spin.

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